

Article

Feasibility Study of Pump Units with Various Direct-On-Line Electric Motors Considering Cable and Transformer Losses

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Featured Application: The presented results can be used to assess the energy-saving potential of general-purpose and industrial electric motors of various types in various applications of electric drives.

Abstract: The high energy intensity of the modern industry determines the high urgency of increasing the energy efficiency of production processes. However, a big number of motor types of enhanced efficiency classes are available on the market. The motor users can be confused about the choice of the right motor solution for a certain application. In this paper, to help with this choice the energy efficiency indicators of various types of electric motors in a low-power pump unit with a constant rotation speed are studied. Moreover, not only power losses in the motor are considered, but also power losses in the cable and transformer, which are influenced by the power factor of the motor. Induction motors (IMs) and synchronous motors powered directly from the grid (direct-on-line synchronous motor with permanent magnet in the rotor, DOL PMSM; direct-on-line synchronous reluctance motor without permanent magnet, DOL SynRM) of IE2, IE3, and IE4 energy efficiency classes are compared. To carry out the analysis, polynomial interpolation of the available catalogue data and experimental data of the motors are used. The main criteria for comparing different motors in this work are the energy savings over the pump's life cycle and the payback period when replacing an IE2 motor with a motor of a higher energy efficiency class. The article shows that although the DOL PMSM has a lower motor efficiency than the DOL SynRM, it saves more energy due to its higher power factor, which reduces cable and transformer losses. It is also shown that, despite the highest initial cost, when taking into account cable and transformer losses, the payback period of DOL PMSM can be shorter than that of IE3 and IE4 induction motors. DOL SynRM has the shortest payback period in all considered cases, has no troublesome rare-earth permanent magnets, and can also be a valuable solution.

Keywords: centrifugal pump; direct-on-line synchronous motor; energy efficiency; induction motor; permanent magnet motor; synchronous reluctance motor

1. Introduction

The high energy intensity of the modern industry determines the high urgency of increasing the energy efficiency of production processes. Electric motors consume about 70% of the electricity in industrial applications. Therefore, in many countries around the world, legislative restrictions on the use of motors with low energy efficiency classes are gradually being introduced. The widespread

use of energy-efficient motors will significantly reduce the energy intensity of the gross national product and greenhouse gas emissions. This is consistent with the targets announced in the energy and environmental strategies of the European Union (European Green Deal [1]), USA (State Energy Program [2]), Switzerland (supporting Paris Climate Agreement [3]), China (supporting Paris Climate Agreement [4]), Japan (Net Zero Energy Building [5]), South Korea (supporting Paris Climate Agreement [6]), and other countries. By now in the European Union, most recently commissioned drives are equipped with induction motors (induction motors, IM, Figure 1a) of energy efficiency class IE3 [7,8].

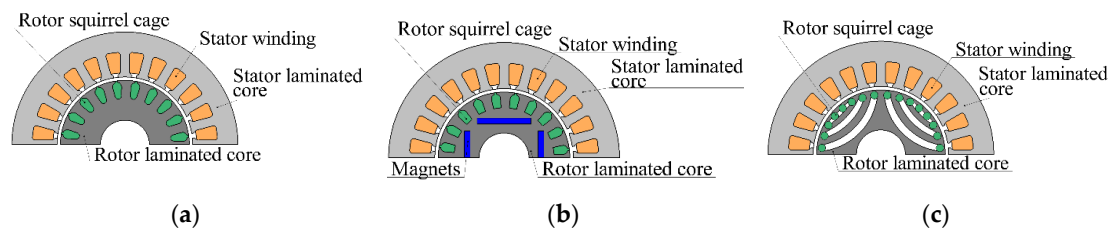


Figure 1. Schematic representation of motor geometry: (a) induction motors, (IM); (b) direct-on-line synchronous motor with permanent magnet in the rotor, (DOL-PMSM); (c) direct-on-line synchronous reluctance motor without permanent magnet (DOL-SynRM).

Moreover, in line with the sustainable development strategy of the European Union (EU), the requirements for the energy efficiency of motors will increase in the coming years. Therefore, already from 1 July 2023, motors with a power of more than 75 kW used in the EU must have an energy efficiency class of at least IE4 [9]. In the future, it is planned to achieve compliance with IE4 class for motors of lower power, as well as achieve compliance with IE5 class for higher power motors [10]. It was already demonstrated that the use of motors with an energy efficiency class higher than IE3 can already be feasible today since they provide significant energy savings and a decrease in greenhouse gas emissions [1].

However, the increase in the demand for motors of higher energy efficiency classes faces significant difficulties in the case of IMs: The sum of the electrical losses in the stator and rotor of IMs is usually greater than the losses in the stator winding of synchronous motors, especially for a power range below 30 kW [8,11]. Increasing the efficiency of induction motors is possible, either by increasing the weight and size of the motor or by using a copper squirrel cage in the rotor [8]. Both of these solutions lead to a significant increase in the cost of the motor. The use of a cast copper rotor cage also significantly complicates the manufacturing process. Therefore, induction motors with a cast copper rotor cage and with direct mains power supply are still not widely used.

In addition to induction motors, some manufacturers [12,13] also offer permanent-magnet synchronous motors with direct mains supply (DOL PMSM, Figure 1b). Typically, an aluminum starting cage is installed on the DOL PMSM rotor for the possibility of starting from the mains. The motor starts as an induction motor and then continues to operate as a synchronous motor, thereby eliminating the main electrical losses in the rotor winding. With reduced rotor losses, these motors can be rated as class IE4.

DOL PMSM characteristics are described in a number of publications [14–19]. However, such motors also do not find widespread use since their cost turns out to be significantly higher than that of IE3 IM due to the use of expensive rare-earth permanent magnets. In addition, the use of rare-earth permanent magnets leads manufacturers to depend on supplies from a specific region since almost all raw materials for the manufacture of rare-earth magnets are imported from mainland China [20]. This factor can also lead to volatility and a sharp rise in prices for rare-earth raw materials, as was the case in the early 2010s [20,21]. Another factor that does not contribute to the widespread use of DOL PMSM is the significant environmental damage caused by the mining of rare-earth metals. It is

known that the extraction of one ton of rare-earth metal concentrate produces 1–1.4 tons of radioactive waste that pollutes the environment [22].

A direct mains powered synchronous reluctance motor (DOL SynRM) does not have the above-mentioned disadvantages of IE4 IM and DOL PMSM. In a number of applications, synchronous reluctance motors (SynRM) which do not have starting squirrel-cage winding and magnets in the rotor are already being used when powered by a frequency converter as a more energy-efficient replacement for IM [23–27]. Several manufacturers offer these motors in conjunction with frequency converters [28–30]. Such SynRMs can correspond to the class IE4 [28,31] or even IE5 [11,25,32], according to [33].

In recent years the scientific literature describes the latest synchronous reluctance motors with energy efficiency class IE4 and above with direct mains supply (DOL SynRM, Figure 1c). Due to the absence of electrical losses in the rotor, DOL SynRM provides higher efficiency in comparison with IM IE3, at a similar production cost [34]. As in the case of DOL PMSM, DOL SynRM is started in asynchronous mode using a squirrel-cage asynchronous winding on the rotor [35–38].

Pumping systems that consume about 22% of all electricity worldwide [39] are one of the applications in which the use of energy-efficient motors is the most promising. Due to the significant cost of the frequency converter, most pumping systems use direct-powered motors [40,41].

Although the topic of comparing the energy efficiency of different types of motors (induction, synchronous reluctance, synchronous motors with magnets) in a pumping application has been covered in a large number of studies, the comparison is usually made for motors powered by a frequency converter [23,27,42–44]. A comparison of the energy consumption of different types of motors in pumps with direct mains supply is considered much less often. For example, Reference [41] compares the energy-efficiency indicators of DOL PMSM and IM of different IE classes in a pump without speed control. In [41], it is also shown that when considering a typical pump cycle, energy consumption is influenced not only by the energy efficiency class of the motor but also by of its efficiency in the modes with a reduced load.

In the article [45], an analysis was performed for a pumping unit with direct power supply from the mains, with a power of 11 kW and two IMs of energy efficiency classes IE1 and IE2. The payback periods (see Section 5) of replacing an electric motor of class IE1 with an electric motor of IE2 class were calculated. However, it should be noted that replacing the IE1 electric motors with IE2 electric motors is obligatory only in some countries. For example, in the countries of the Eurasian Economic Union (Russia, Kazakhstan, Belarus, Kyrgyzstan, Armenia) legislation in the field of energy efficiency until 1 September 2021 does not prohibit the use of IE1 class motors [46].

Another important factor that is not considered in [23,41] when analyzing the energy efficiency of pumping systems is that there are power losses in the power line. Typical elements of a power transmission line are cables and transformers, the losses of which depend on the power factor of the motor. When the power factor decreases, the reactive component of the current as well as the total current increases. A number of works [47–49] report that DOL SynRM has a lower power factor compared to IM and DOL PMSM, which can lead to increased cable and transformer losses. Therefore, the study of the quantitative influence of the efficiency and power factor of the motor on the indicators of energy consumption is one of the goals of this work.

In our previous work [50], the energy efficiency of the pump drive is assessed taking into account the losses in the cable without taking into account the losses in the transformer. Various load points of the motor were considered, corresponding to a typical pump cycle without speed control. The paper compares annual and lifecycle energy consumption for IM, DOL PMSM, and DOL SynRM (Figure 1). All three types of motors under consideration have a similar stator design, but different rotor design. All motors have a short-circuited aluminum winding on the rotor and an asynchronous start. However, DOL PMSM (Figure 1b) when the speed is close to the nominal switches to the synchronous operation mode due to the synchronizing torque of the permanent magnets. DOL SynRM (Figure 1c) also enters synchronous mode after starting due to the synchronizing torque provided by the magnetic anisotropy

of the rotor. Due to the absence of basic (fundamental) electrical losses in the rotor, when operating in synchronous mode, DOL PMSM and DOL SynRM usually have a higher efficiency than IM. In [50], it is shown that the power factor of the motor has a significant effect on the losses in the cable and on the energy consumption of the system as a whole. Therefore, when choosing different types of motors, it is important to consider not only their efficiency and energy efficiency class, but also their power factor. However, in [50] the losses in the transformer are not taken into account. Transformer losses can significantly depend on the reactive component (power factor) on the load.

Low-power pump units usually operate in groups as a part of a pumping station powered through a common cable and connected to a transformer [51]. The losses in this transformer should be considered while calculating the energy efficiency of the pumping system. The aim of this paper is to perform further analysis of the various motor types described in [50] taking into account not only the losses in motors and cables but also losses in the transformer. The main criteria for comparing motors are: (1) energy and cost savings during the pump life cycle and (2) payback period. While assessing the payback period, replacing an IE2-motors with a motor of a higher efficiency class is considered. Both the use of a more energy-efficient motor in a new pump unit being put into operation and the replacement of the motor in a pump unit in operation are considered.

2. Evaluating Pump Energy Consumption

In this section, the analytical dependencies used for evaluating the energy efficiency indicators of the motors are described. Figure 2 demonstrates the diagram of the considered pump unit that includes a centrifugal pump and an electric motor powered from the medium-voltage power supply via a step-down transformer. The electric motor is coupled to the pump without intermediate mechanical transmissions. The electrical power P_1 consumed by the pump unit from the grid can be determined as the following [40]:

$$P_1 = \eta_{motor} \cdot P_{mech} + p_{cable} + p_T; \quad (1)$$

$$P_{mech} = \eta_{pump} \cdot P_{hydr} = \eta_{pump} \cdot \rho \cdot g \cdot H \cdot Q = f(Q), \quad (2)$$

where Q is the required flowrate; H is the hydraulic head defined from H - Q characteristic of the pump from the catalogue; g is the acceleration of gravity; ρ is the density of a liquid; P_{hydr} is the hydraulic power of the pump; P_{mech} is the input mechanical power of the pump, $f(Q)$ is its dependence on Q obtained from the catalogue; η_{pump} is the pump efficiency; η_{motor} is the motor efficiency; p_{cable} is the electrical loss in the cable; p_T is the electrical loss in the transformer.

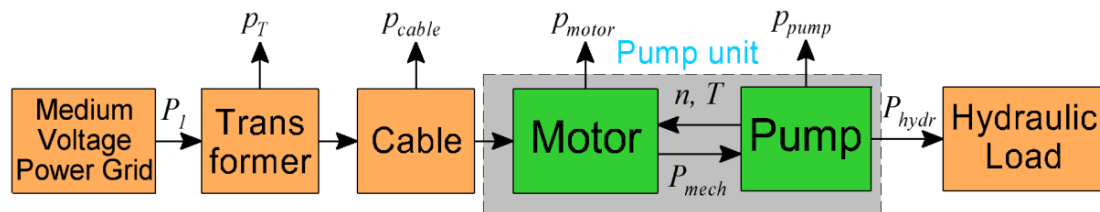


Figure 2. Diagram of a single pump unit for fixed-speed operation.

Not only the losses in the motor considered but also the losses in the transmission line elements: the cable and transformer. The loss in the cable depends on the phase resistance of the cable and the RMS motor current [52]:

$$p_{cable} = 3 \cdot R_{cable} \cdot I_{motor}^2, \quad (3)$$

where R_{cable} is the cable phase resistance; I_{motor} is the motor current.

The RMS motor current can be found as the following:

$$I_{motor} = P_{mech} / (\sqrt{3} \cdot V_{motor} \cdot \cos \varphi \cdot \eta_{motor}), \quad (4)$$

where $V_{motor} = 400$ V is the line grid voltage; $\cos\varphi$ and η_{motor} are the motor power factor and efficiency, according to data from the manufacturer's catalogue.

The transformer losses p_T can be calculated using the manufacturer's data as shown in Section 4. To calculate the mechanical power P_{mech} , the pump characteristics from the manufacturer's datasheets were used [53]. Adjusting the flowrate using a throttling valve is assumed. The characteristics of a centrifugal pump B-NM4 65/25B/B (manufactured by Calpeda S.p.A., Montorso Vicentino, Vicenza, Italy) with the rated power $P_{rate} = 4$ kW and with the rated rotational speed $n = 1450$ rpm was assumed for the calculation [53]. The pump data are specified in Table 1. Q_{BEP} denotes the flow at the best efficient point (BEP), and H_{BEP} denotes the pump head at BEP.

Table 1. Published characteristics of pump from manufacturer.

Type	P_{rate} , W	n_{rate} , rpm	Q_{BEP} , m ³ /h	H_{BEP} , m	Pump Efficiency (BEP), %
B-NM4 65/25B/B	4000	1450	60	15.4	75.5

In this study, five four-pole electric motors with the rated power of 4kW are compared, namely DOL SynRM (a test prototype [35]), DOL PMSM (manufacturer WEG [54]), and induction motors of three different efficiency classes (manufacturers WEG and Siemens [55–57]). The efficiency and the power factor of the DOL PMSM and the IMs were taken from the datasheets.

There are still no commercially available high-performance DOL SynRMs on the market to the best of our knowledge. ABB Group corporation has announced the launch of IE4 class DOL SynRM [58] production, however, at the moment of writing this manuscript, these motors are still not available on the market. For this reason, to evaluate the characteristics of a DOL SynRM, the data of the experimental sample described in [35] were assumed.

Various characteristics of the motors are demonstrated in Table 2, Table 3, and Figure 3. The motor efficiency is specified in Table 3 and Figure 3a. The motor power factor is specified in Table 3 and Figure 3b. The RMS current for the considered motors is compared in Figure 3c. The motor current is calculated using Equation (4).

Table 2. Motor characteristics.

Type of Motor	Rated Mechanical Power, W	Poles	Frame Size	Frame Material	Wight, kg	Rated Voltage, V
DOL SynRM	4000	4	IEC 112	No data	No data	400
DOL PMSM	4000	4	IEC 112	Cast iron	49	400
IE2 IM	4000	4	IEC 112	Cast iron	45.1	400
IE3 IM	4000	4	IEC 112	Cast iron	42	400
IE4 IM	4000	4	IEC 112	Cast iron	58	400

Table 3. Motor characteristics.

Type of Motor	Motor Efficiency, %			Motor Power Factor		
	50% Load	75% Load	100% Load	50% Load	75% Load	100% Load
DOL SynRM	91.6	92.4	91.9	0.607	0.713	0.755
DOL PMSM	89.0	91.0	91.7	0.68	0.81	0.88
IE2 IM	86.0	86.7	86.7	0.62	0.74	0.8
IE3 IM	88.7	89.1	88.8	0.6	0.72	0.78
IE4 IM	91.0	91.6	91.1	0.63	0.75	0.81

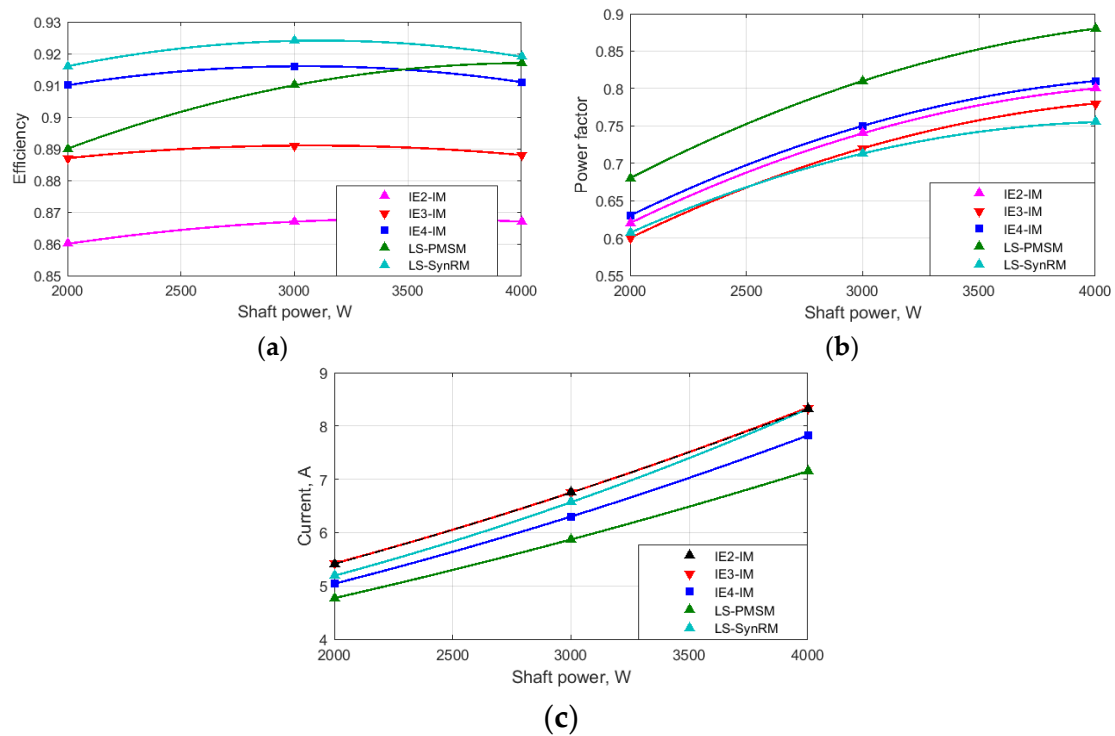


Figure 3. Motor characteristics vs. motor shaft power: (a) efficiency; (b) power factor; (c) current.

In Figure 3a, it can be seen that DOL SynRM has the highest efficiency over the whole loading range. The efficiency of the DOL PMSM in the rated loading point (4000 W) is very close to that of the DOL SynRM, but at partial loads, the DOL PMSM's efficiency decreases much faster than that of DOL SynRM. In Figure 3b, it can be seen DOL PMSM has the highest power factor over the whole loading range. The power factors of IE3 IM and DOL SynRM are close and significantly lower than the one for PMSM. The power factors of IE2 IM and IE4 IM are slightly higher than those of IE3 IM. The rate of power factor decrease with a decrease in load is approximately the same for all studied motors: When the load was decreased from 100% to 50% the power factor decreased by approximately 0.15.

3. Pump Operating Cycle

According to reference [59], in this study, a duty cycle (flowrate versus time) was assumed for the system that is typical for centrifugal pumps with an uncontrolled speed and approximately constant flowrate. In practice, even in the case of fixed-speed pumps, the required flowrate rarely remains constant. For instance, even for the simplest pumping application, when a pump moves fluid from one tank to another, the pump operating point will vary as the level of water in the tank also changes. Therefore, the pump does not operate at the best efficiency point all the time. Figure 4 shows the assumed operating cycle for a pump with approximately constant flowrate, according to [59].

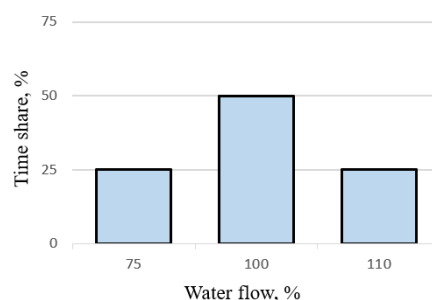


Figure 4. Pump loading diagram.

Since the electric motor is powered directly from the electric grid and the rotational speed cannot be adjusted, it is assumed that the flow is regulated by throttling. In this case, the pump operating point will move along the Q - H curve from the catalogue until the intersection with the hydraulic load curve. Figure 5a shows three intersection points for the considered loading conditions (75%, 100% and 110% of Q_{BEP}) for the Q - H curve according to the catalogue data for the selected pump [53].

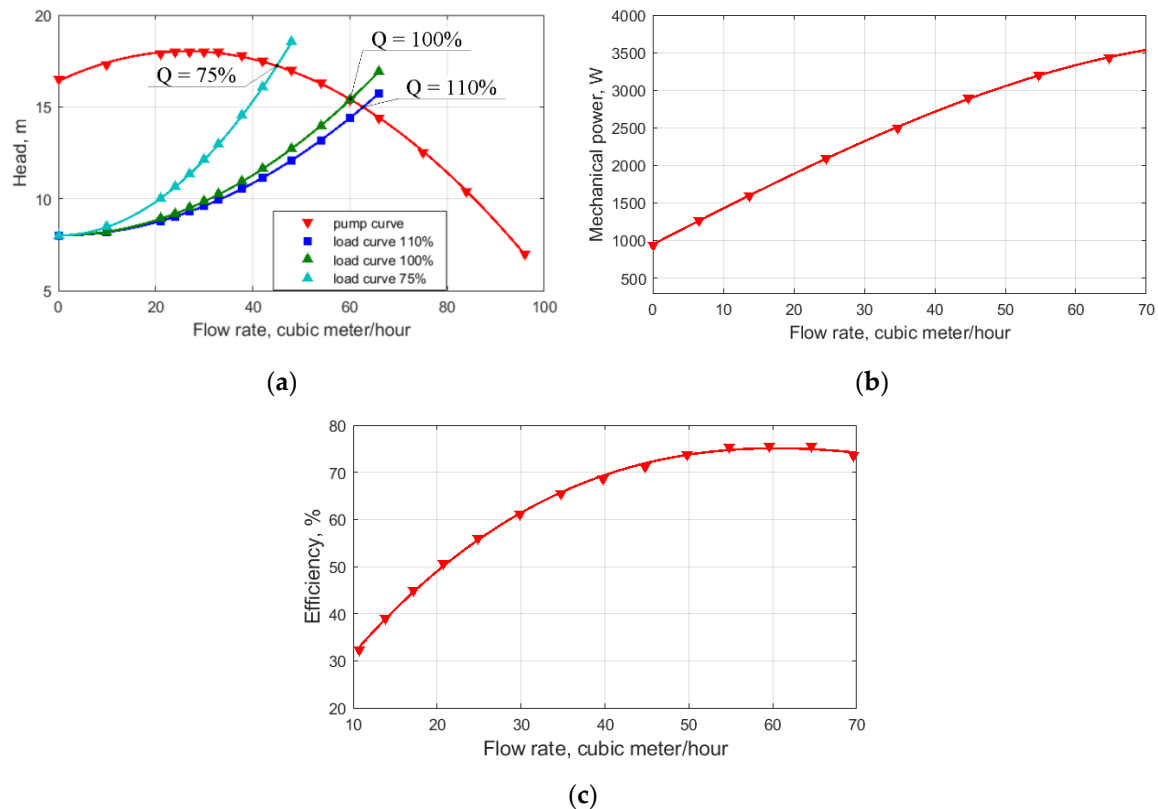


Figure 5. Pump performances: (a) Q - H curve; (b) pump mechanical power; (c) pump efficiency.

The mechanical (input) power curve of the pump as a function of the flow is also specified in the catalogue (Figure 5b). The mechanical power P_{mech} loading the motor was obtained from this curve for three considered operation points (75%, 100% and 110% of Q_{BEP}). The flow corresponding to 100% of the maximum flow in the pump operating cycle was chosen at the best efficiency point (maximum efficiency of the pump, $Q = 60 \text{ m}^3/\text{h}$, $\eta_{pump} = 0.755$) and determined based on the pump efficiency curve (Figure 5c) [53]. The efficiencies of the electric motors under the three considered loading conditions were found using polynomial interpolation of the efficiency data of Table 3. The obtained interpolated efficiencies are demonstrated in Table 4. Table 4 also shows the following characteristics for each considered operating point: flow, hydraulic head, mechanical power, motor torque, and pump efficiency.

Table 4. Characteristics of the pump duty cycle.

$Q, \%$	$Q, \text{m}^3/\text{h}$	H, m	P_{mech}, W	$T, \text{N}\cdot\text{m}$	Pump Efficiency, %	Motor Efficiency				
						DOL SynRM	DOL PMSM	IE2 IM	IE3 IM	IE4 IM
110	66	14.4	3453	22.0	75	0.924	0.915	0.867	0.89	0.91
100	60	15.4	3335	21.2	75.5	0.925	0.914	0.868	0.891	0.91
75	45	17.25	2962	18.9	71.4	0.925	0.909	0.868	0.891	0.908

4. Transformer and Cable Losses Depending on Motor Power Factor

An important energy parameter for a motor powered directly by mains is not only the efficiency but also the power factor, because the reactive current feeding a motor flows not only through its winding but also through elements of an electric transmission line from which a motor receives power. This causes additional losses [60]. Since the considered motors have different power factors and total currents (see Figure 3b,c and Table 3), it is necessary to evaluate the influence of the power factor on the cost of electricity for the consumer.

The following structure of the electrical system is considered for calculations: three pump units with a capacity of 4kW connected to the mains via a 100 m cable and a 16 kVA step-down transformer (see Section 5). Losses in the cable sections connecting the individual pump units to the common point of three pump units are not taken into account. Thus, the current creating losses in the cable and transformer can be found as the sum of the currents of individual pump units:

$$I_{load} = I_{motor\ 1} + I_{motor\ 2} + I_{motor\ 3} = 3 \cdot I_{motor}, \quad (5)$$

where $I_{motor\ 1} \dots I_{motor\ 3}$ are the motor currents of pump units of the considered electrical system; I_{motor} is the phase current of one of these motors.

The results of the calculation of the load current of the cable and transformer for various studied pump operating points are presented in Table 5. Single motor current is calculated using polynomial data interpolation Figure 3c. The total load current is then calculated using the Formula (5). In the considered case (see Section 5), it is necessary to calculate the cable and transformer losses, which depend on the load current.

Table 5. The current of three motors with various loading conditions of the duty cycle.

$Q, \%$	P_{mech}, W	I_{load}, A				
		DOL SynRM	DOL PMSM	IE2 IM	IE3 IM	IE4 IM
110	3453	22.0	19.3	22.3	22.3	20.8
100	3335	21.4	18.8	21.7	21.7	20.3
75	2962	19.5	17.5	20.1	20.1	18.8

For industry, the typical cable length for connecting low-voltage power equipment is about 0.1 km [61]. Many low-voltage feeders operate with loads that exceed those planned for the initial design and are close to the maximum allowable load due to the inevitable increase in consumer energy demand in 10–20 years and the delayed process of the upgrade of transmission lines [62]. Considering this fact, in low-power electrical facilities with a current load of up to 24 A, three-phase cables with PVC insulation and with a cross-section of 2.5 mm² can be used [63]. The specific resistance of one phase of a copper cable with these parameters is approximately $\rho_{cable} = 7.55 \text{ Ohm/km}$. The reactance in the calculation of stranded cables of small cross section is usually neglected. The phase resistance of such a cable will be $R_{cable} = L_{cable} \cdot \rho_{cable} = 0.1 \cdot 7.55 = 0.755 \text{ Ohm}$. Losses in the cable are calculated from (3). The losses in the transformer with the parameters of 400 V and 16 kVA are calculated based on the manufacturer's data as [64]:

$$P_T = A + B \cdot (I_{load}/I_{T\ rate})^2, \quad (6)$$

where $I_{T\ rate} = 23.1 \text{ A}$ —nominal phase current of the transformer; $A = 40 \text{ W}$ and $B = 440 \text{ W}$ are determined based on the value of the transformer losses at $I_{load} = 0.5 \cdot I_{T\ rate}$ and $I_{load} = I_{T\ rate}$ (150 and 480 W, correspondingly, according to [64]).

Figure 6 shows the losses in these elements, calculated by the Formulas (3) and (6). Using the above functions, the losses were calculated in various components of the pumping system (motors, cable, and transformer). Figure 7 shows the results of calculating these losses depending on the flowrate and the type of motor.

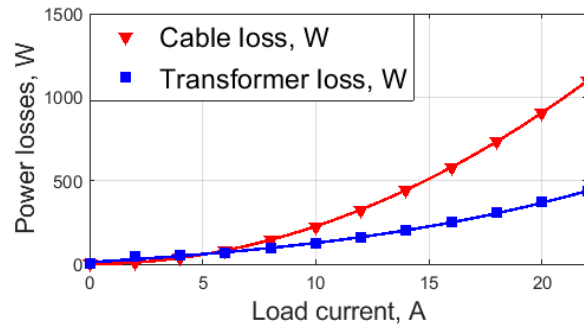


Figure 6. Cable and transformer losses depending on the load current.

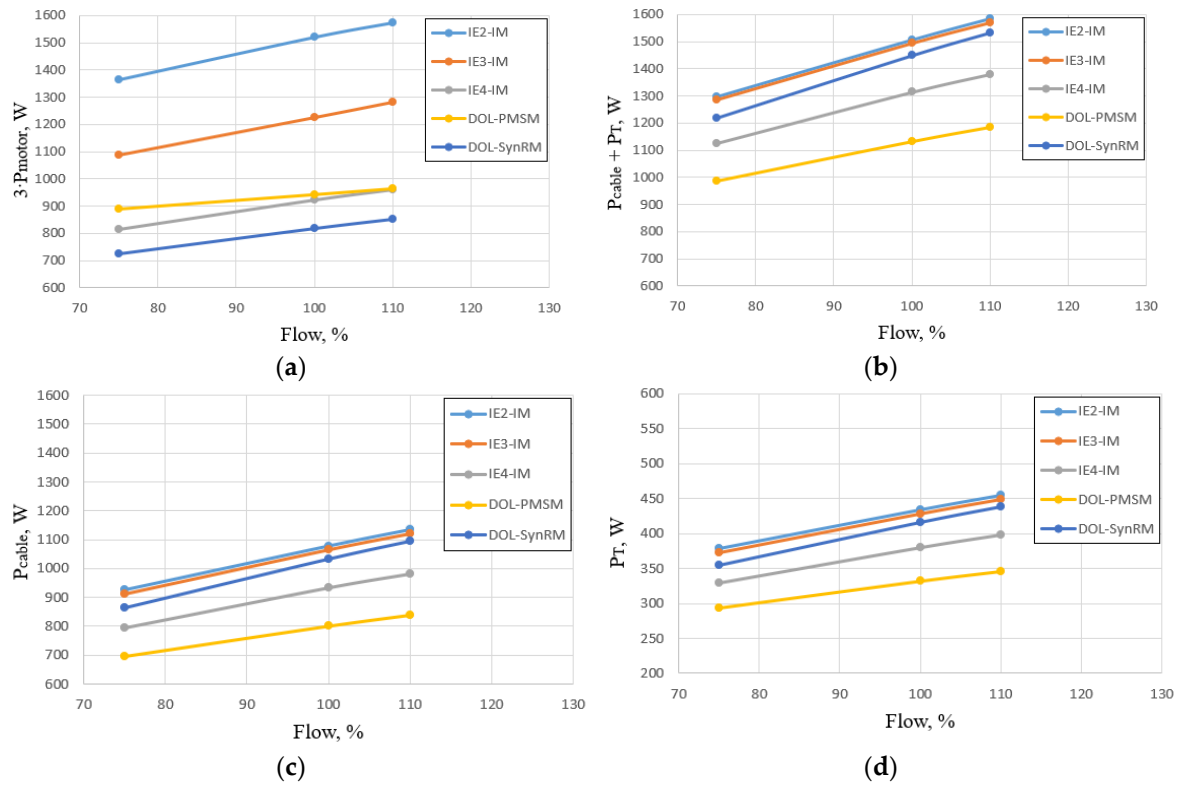


Figure 7. Power losses at three points of the pump duty cycle with various flows: (a) motors; (b) cable + transformer; (c) cable; (d) transformer.

It can be seen that the sum of the losses in the cable and the transformer ($p_{cable} + p_T$) in all cases, except for the IE2 motor, turns out to be greater than the losses in the three motors of the $3 \cdot P_{motor}$. The value ($p_{cable} + p_T$) for IE2 IM, IE3 IM differs little. Using IE4 IM and DOL PMSM can reduce ($p_{cable} + p_T$) for about 12 by 25%, respectively. These results confirm the importance of the power factor increase for the reduction of the energy consumption of the motors powered directly from the grid.

5. Pump Unit Lifetime Energy Costs

Using the results obtained in the previous sections, the energy-saving indicators are calculated for various cases: excluding losses in the cable and the transformer (Figure 8a), taking into account losses in the cable only (Figure 8b), and taking into account the cable and transformer losses (Figure 8c). The daily energy consumption of an electric motor for the whole operating cycle (see Figure 4) can be found as the following:

$$E_{day} = t_{\Sigma} \cdot \sum_{i=1}^3 (P_{1i} \cdot t_i / t_{\Sigma}). \quad (7)$$

where $i = 1 \dots 3$ is the index of a loading point; P_{1i} is the eclectic power P_1 in i -th loading point; t_i is the operation time of a loading point; t_Σ is the whole time period (24 h).

Then the annual energy consumption can be obtained according (8):

$$E_{year} = E_{day} \cdot 365. \quad (8)$$

The cost of electricity consumed (in Euro), considering the applied grid tariffs $GT = 0.2036 \text{ €/kW}\cdot\text{h}$ for non-household consumers [65] for Germany in the second half of 2019, was calculated as follows:

$$C_{year} = E_{year} \cdot GT. \quad (9)$$

The expected lifetime of a pump is often evaluated to be about 20 years [66,67]. In this section, the energy cost is estimated for a service life of $n = 20$ years, excluding maintenance costs and the initial cost of the motors. The net present value (NPV) of the lifecycle cost was obtained as follows:

$$C_{LCC} = \sum_{j=1}^n (C_{year j} / [1 + (y - p)]^j), \quad (10)$$

where $C_{year j}$ is the energy cost of j th year; y is the interest rate ($y = 0.04$); p is the expected annual inflation ($p = 0.02$); n is the lifetime of the pump unit ($n = 20$ years) [67].

Life cycle cost savings S_{LCC} for a given motor is calculated according to (11):

$$S_{LCC} = C_{LCC} - C_{LCC IE2}, \quad (11)$$

where C_{LCC} is the lifecycle electricity cost of the considered motor; $C_{LCC IE2}$ is the lifecycle electricity cost of the IE2 IM.

S_{LCC} percentage is calculated according to (12):

$$S_{LCC} = 100\% \cdot (C_{LCC} - C_{LCC IE2}) / C_{LCC IE2}, \quad (12)$$

Results based on Equations (1)–(12), for three different cases (Figure 8) are presented in Tables 6–8. For ease of comparison, in all cases, the results of the energy consumption of the pumping station consisting of three motors (denoted as “x3”) are presented. The structure shown in Figure 8c illustrates the power supply of a typical pumping station [68]. The number of the pump units in one pumping station can be different, usually it is 3 or more. The structures in Figure 8a,b are simplified models of the structure in Figure 8c without taking into account the losses in the supply cable and transformer (Figure 8a) and taking into account only the losses in the cable, without taking into account the losses in the transformer (Figure 8b). The simplified structures are considered to assess the impact of the cable and transformer losses on the results of the comparison of electric motors of various types.

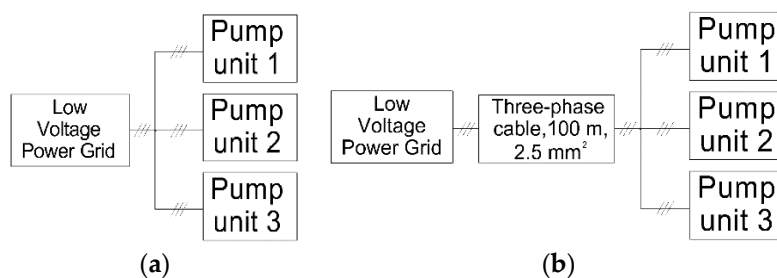


Figure 8. Cont.

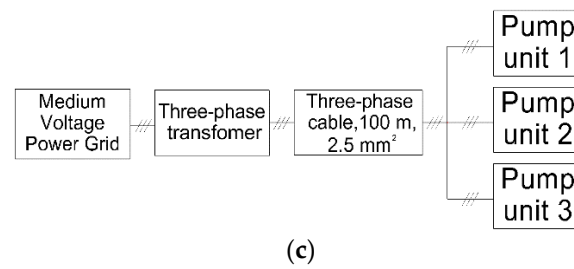


Figure 8. Structure of the considered electric system: (a) case 1; (b) case 2; (c) case 3.

To analyze the effect of losses in the cable and transformer, we will compare the results for different motors in the three considered cases (Tables 6–8). The results are presented in Table 9 and Figure 9.

Based on the results shown in Table 9 and Figure 9, it can be concluded that taking into account the power factor of the motor and losses in the power transmission line significantly affects the results of comparing motors of different types. The pump lifetime cost often consists mostly of the energy cost (>50–60%) [66,67]. On the other hand, according to [66,67], the maintenance costs comprise only 3–13% of the overall lifetime cost. Moreover, it is accepted that the maintenance costs of the pump unit do not depend on the motor type. For this reason, the maintenance costs of the pump unit are not taken into account in the lifetime cost calculation in this study.

Table 6. Calculation of the energy consumption of one pump unit excluding the cable and transformer losses (case 1, $m = 1$) [50].

	i	t_i/t_Σ , %	DOL SynRM $\times 3$	DOL PMSM $\times 3$	IE4 IM $\times 3$	IE3 IM $\times 3$	IE2 IM $\times 3$
P_1 , W	1	25	11,210	11,321	11,320	11,639	11,934
	2	50	10,822	10,946	10,928	11,229	11,881
	3	25	9612	9776	9701	9973	11,722
E_{day} , kW·hour			255	258	264	257	285
E_{year} , kW·hour			93,000	94,148	96,515	93,901	103,844
Annual energy savings, kW·hour			3615	3232	3315	2443	–
Annual cost savings C_{year} , €			736	658	675	497	–
Life cycle energy cost C_{LCC} , k€ (per 20 years)			103.2	104.5	104.2	107.1	115.2
Life cycle cost savings S_{LCC} , k€ (per 20 years)			12.0	10.8	11.0	8.13	–
Life cycle cost savings S_{LCC} , % (per 20 years)			10.4	9.3	9.6	7.1	–

Table 7. Calculation of the energy consumption of three pump units considering the cable loss (case 2, $m = 2$).

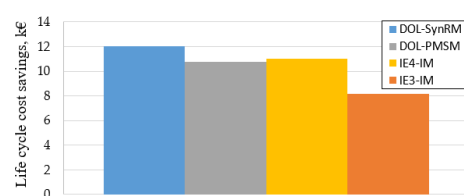
	i	t_i/t_Σ , %	DOL SynRM $\times 3$	DOL PMSM $\times 3$	IE4 IM $\times 3$	IE3 IM $\times 3$	IE2 IM $\times 3$
P_1 , W	1	25	12,305	12,162	12,302	12,762	13,057
	2	50	11,856	11,748	11,862	12,295	12,946
	3	25	10,476	10,471	10,497	10,886	12,634
E_{day} , kW·hour			279	277	279	289	309
E_{year} , kW·hour			101,817	101,021	101,887	105,638	112,967
Annual energy savings, kW·hour			3717	3982	3693	2443	–
Annual cost savings C_{year} , €			757	811	752	497	–
Life cycle energy cost C_{LCC} , k€ (per 20 years)			113.0	112.1	113.1	117.2	125.4
Life cycle cost savings S_{LCC} , k€ (per 20 years)			12.4	13.3	12.3	8.13	–
Life cycle cost savings S_{LCC} , % (per 20 years)			9.9	10.6	9.8	6.5	–

Table 8. Calculation of the energy consumption of three pump units considering the cable and transformer losses (case 3, $m = 3$).

	i	t_i/t_Σ , %	DOL SynRM $\times 3$	DOL PMSM $\times 3$	IE4 IM $\times 3$	IE3 IM $\times 3$	IE2 IM $\times 3$
P_1, W	1	25	12,744	12,508	12,700	13,211	13,505
	2	50	12,272	12,080	12,242	12,723	13,374
	3	25	10,830	10,764	10,828	11,258	13,007
E_{day} , kW·hour			289	285	288	299	320
E_{year} , kW·hour			105,379	103,875	105,146	109,311	116,641
Annual energy savings, kW·hour			3754	4255	3832	2443	–
Annual cost savings C_{year} , €			764	866	780	497	–
Life cycle energy cost C_{LCC} , k€ (per 20 years)			116.9	115.3	116.7	121.3	129.4
Life cycle cost savings S_{LCC} , k€ (per 20 years)			12.5	14.2	12.8	8.13	–
Life cycle cost savings S_{LCC} , % (per 20 years)			9.7	10.9	9.9	6.3	–

Table 9. Results of the life cycle costs for various considered cases.

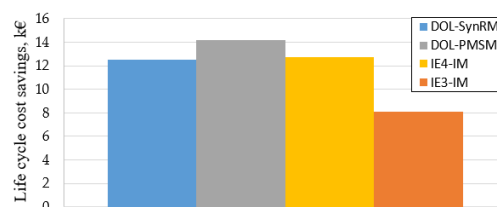
Motor	Case Number, m	Annual Cost Savings C_{year} , €	Life Cycle Energy Cost C_{LCC} , k€ (per 20 years)	Life Cycle Cost Savings, S_{LCC} , k€ (per 20 years)	Life Cycle Cost Savings, S_{LCC} , % (per 20 years)
DOL SynRM	1	736	103.2	12.0	10.4
	2	757	113.0	12.4	9.9
	3	764	116.9	12.5	9.7
DOL PMSM	1	658	104.5	10.8	9.3
	2	811	112.1	13.3	10.6
	3	866	115.3	14.2	10.9
IE4 IM	1	675	104.2	11.0	9.6
	2	752	113.1	12.3	9.8
	3	780	116.7	12.8	9.9
IE3 IM	1	497	107.1	8.1	7.1
	2	497	117.2	8.1	6.5
	3	497	121.3	8.1	6.3



(a)



(b)



(c)

Figure 9. Life cycle cost savings (20 years) using various motor types: (a) case 1 (without cable and transformer losses); (b) case 2 (3 pump units, considering the cable loss); (c) case 3 (3 pump units, considering the cable and transformer losses).

As seen in Figure 9, the IE3 IM provides a life cycle cost savings S_{LCC} of 8.1 k€ with respect to the IE2 IM. However, the amount of savings (8.1 k€) for the IE3 IM is the same for all three considered cases $m = 1-3$ since the losses in the cable and transformer for the IE3 IM and the IE2 IM differ little (Figure 7). If the losses in the cable and the transformer are not taken into account (first case, $m = 1$), the savings are greater for the DOL SynRM than for the DOL PMSM and the IE4 IM. Thus, the lifetime savings for the DOL SynRM are 12 k€, that is 1.2 k€ higher than for the DOL PMSM; 1.0 k€ higher than for the IE4 IM; and 3.9 k€ higher than for the IE3 IM (Figure 9a).

However, when taking into account the cable and transformer losses (second and third cases, $m = 2, 3$), the DOL PMSM and the IE4 IM provide greater savings than the DOL SynRM. In the third case, $m = 3$, the DOL PMSM and the IE4 IM provide 2.2 k€ and 0.8 k€ greater savings, respectively than the DOL SynRM (Figure 9c). The DOL PMSM, in this case, provides the maximum savings among all motors, which is 14.2 thousand € (SLCC = 10.9% higher with respect to the IE2 IM). However, as we have already mentioned above, the DOL PMSM and the IE4 IM have a higher initial cost compared to the IE3 IM and the DOL SynRM. In addition, the DOL PMSM uses rare-earth magnets in its design while the rare-earth elements processing from raw ore is associated with significant environmental damage [22].

The IE4 IM and the DOL SynRM provide savings of 12.8 and 12.5 k€ respectively, which is 9.9% and 9.7%, greater with respect to the IE2 IM. Therefore, their use is significantly more profitable than using the the IE3 IM. The latter gives only 8.1 k€ of savings or 6.3% greater with respect to IE2 IM. Although the efficiency of the IE4 IM is lower than that of the DOL SynRM, it provides energy savings of $9.9\% - 9.7\% = 0.2\%$ over 20 years compared to the DOL SynRM. The DOL PMSM provides savings of $10.9\% - 9.7\% = 1.2\%$ over 20 years compared to DOL SynRM.

While comparing $m = 2$ and $m = 3$ cases, it can be seen that taking into account the transformer losses in addition to the cable losses increases the calculated savings due to improved power factor when using DOL PMSM and IE4 IM. Therefore, adding in the transmission line elements which cause additional losses (transformers, cables, etc.) leads to increased savings for the DOL PMSM and the IE4 IM. Thus, for the DOL PMSM life cycle cost savings increase from 13.3 to 14.2 k€ when changing from $m = 2$ to $m = 3$, respectively. Similarly, for IE4 IM life cycle cost savings increase from 12.3 to 12.8 k€ when changing from $m = 2$ to $m = 3$, respectively.

Figure 10 also illustrates the time dependencies on the total costs and the cost savings of different motors in case 3 when both the cable and transformer losses are considered.

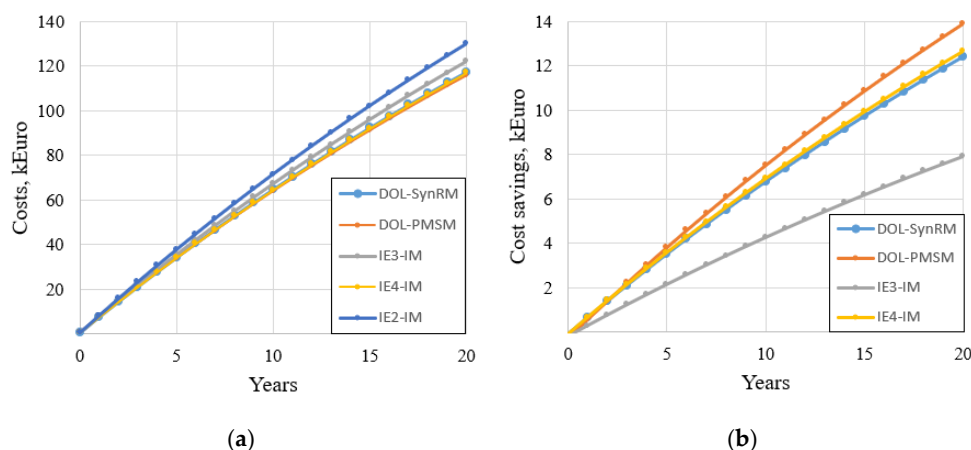


Figure 10. Time dependencies for different motors (case 3): (a) cost vs. time; (b) cost savings compared with IE2 motor vs. time.

6. Initial Cost and Payback Period of the Motors

Since the motors have different initial costs, it is necessary to compare not only the energy savings they provide but also their payback period. When calculating the payback period, 2 cases are

considered: (1) the case of using a higher class motor instead of an IE2 class motor when a new pump unit is commissioned; (2) the case of replacement of an IE2 class motor with a motor of a higher energy efficiency class in a pump unit in service. The initial investment cost of the 4kW, the 4-pole IE2 IM is assumed to be 406.1 € [69].

Studies [70,71] show that the difference in the market value of the IMs of neighboring energy efficiency classes is usually in the range of 15–30%. A comparison of market price information for specific IM models confirms these findings. For this calculation, we will assume that the IE3 IM price is 22.5% higher than the IE2 IM price. Let us also assume that the IE4 IM price is 22.5% higher than the IE3 IM price.

In the literature, there are various estimates of the increase in the cost of the DOL PMSM in comparison to the IE3 IM. Thus, in [70] it is said about the increase in cost by 100%. However, the authors of this paper see no objective reason for such a large increase in cost: Comparison of information on market prices for specific models, as a rule, leads to a difference in the price of IE3 IMs and DOL PMSMs in the range of 30–40%. For this calculation, we will assume that the price of the DOL PMSM is 35% higher than the price of the IE3 IM. Many studies point out that there are no objective reasons for a significant difference in the cost of DOL SynRMs and IE3 IMs [35,36,38,70]. For this calculation, we will assume that the DOL SynRM price is equal to the IE3 IM price.

Comparing the initial cost of the motors with the savings in electricity costs calculated in the previous section for case 3 (taking into account the losses in the cable and transformer), we calculate the payback periods of various motors when a new pump unit is put into operation, as:

$$T_{\text{payback}} = (C_{\text{IE2}} - C_{\text{motor}}) / C_{\text{year}}, \quad (13)$$

where C_{motor} is the initial cost of the considered motor; C_{IE2} is the initial cost of the efficiency class IE2 motor; C_{year} is the motor annual energy savings.

Table 10 and Figure 11 show the results of calculating the payback period when commissioning a new pump unit. In this case, the payback period for all motors is less than six months. This confirms the high profitability of using energy-efficient motors in new installations. Taking into account the losses in the cable and the transformer, the difference between the payback periods for the IE4 IM and the DOL PMSM (compare the heights of the corresponding columns of the diagrams in Figure 11a,c) is significantly reduced compared to the DOL SynRM. The DOL SynRM has the lowest payback period of 0.12 years.

Table 10. Results of the payback period (the case of a new pump unit commissioning).

Value	DOL SynRM	DOL PMSM	IE4 IM	IE3 IM	IE2 IM
Initial cost C_{motor} , €	497.5	671.6	609.4	497.5	406.1
Payback period, years (case 1)	0.124	0.403	0.301	0.184	–
Payback period, years (case 2)	0.121	0.327	0.270	0.184	–
Payback period, years (case 3)	0.120	0.306	0.261	0.184	–

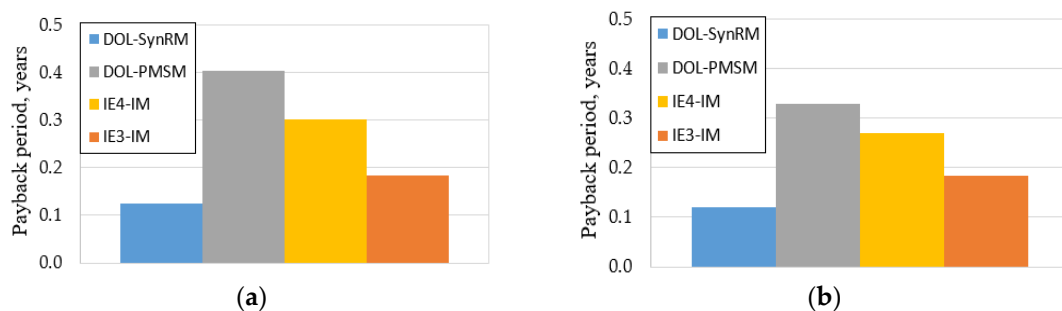


Figure 11. Cont.

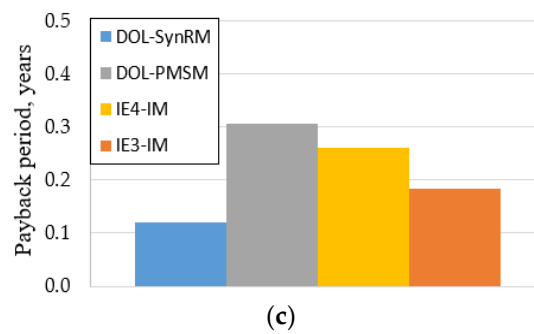


Figure 11. Payback period of various motor types (the case of a new pump unit commissioning): (a) case 1 (without cable and transformer losses); (b) case 2 (3 pump units considering the cable loss) (c) case 3 (3 pump units considering the cable and transformer losses).

When a new pump unit is put into operation the use of an IE3 class motor can be reasonable in the very short term. Its payback period is 2.2 months (0.184 years), which is less than that of the IE4 IM and the DOL PMSM. However, in the longer term, namely 4 months (0.33 years), the IE4 IM and the DOL PMSM appear to be more cost-effective (see Table 10). To calculate the payback period for replacing an IE2 motor in a pumping system, the following expression is used:

$$T_{\text{payback}} = C_{\text{motor}} / C_{\text{year}} \quad (14)$$

Figure 12 and Table 11 show the results of calculating the payback period after replacing a motor in a pumping system in operation. In this case, despite the high initial cost, when taking into account losses in the cable and transformer (case 3, $m = 3$, Figure 12c), the DOL PMSM and the IE4 IM have practically equal payback periods of 0.78 years. The IE3 IM is the least profitable when replacing the IE2 IM, since its payback period is 1 year. Despite the fact that when using the DOL SynRM, the losses in the cable and transformer are greater than in the cases of the DOL PMSM and the IE4 IM, in all cases under consideration the DOL SynRM has the shortest payback period. Thus, for $m = 3$, the payback period for the DOL SynRM is only 0.65 years.

Table 11. Results of the payback period (the case of replacing the motor in an exploiting pump unit).

Value	DOL SynRM	DOL PMSM	IE4 IM	IE3 IM
Initial cost C_{motor} , €	497.5	671.6	609.4	497.5
Payback period (case 1), years	0.68	1.02	0.90	1.00
Payback period, years (case 2)	0.66	0.83	0.81	1.00
Payback period, years (case 3)	0.65	0.78	0.78	1.00

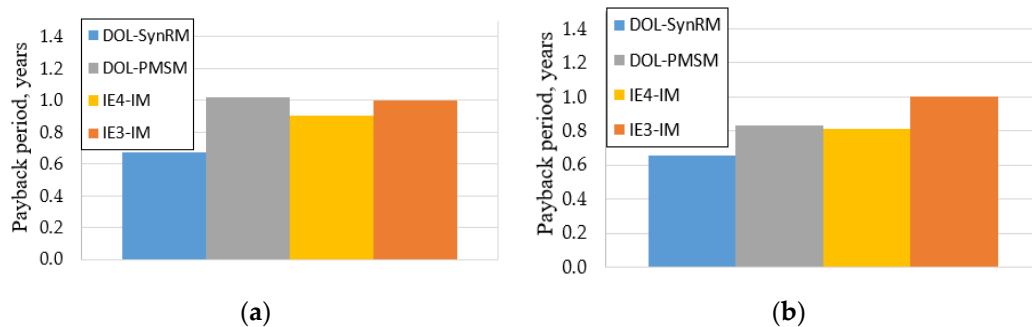


Figure 12. Cont.

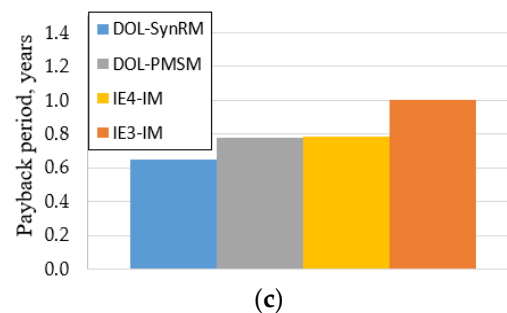


Figure 12. Payback period of various motor types (the case of replacing the motor in an exploiting pump unit): (a) case 1 (without cable and transformer losses); (b) case 2 (3 pump units considering the cable losses); (c) case 3 (3 pump units considering the cable and transformer losses).

One could see that when the losses in the cable and the transformer are taken into account, the use of motors with a higher power factor becomes more profitable since the payback period is reduced. Thus, for $m = 1$, that is excluding cable and transformer losses (Figure 12a), the DOL PMSM payback period is 1.02 years. However, for $m = 2$, which means including the cable losses (Figure 12b), the payback period is 0.83 years. Moreover for the third case, $m = 3$, including losses in the cable and the transformer (Figure 12c), the payback period is even lower, 0.78 years. This is due to the increase in the absolute values E_{year} and C_{year} , when taking into account the losses not only in the motor but also in the cable and the transformer.

7. Conclusions

In this study, energy efficiency indicators were evaluated such as life cycle energy savings, cost savings, and payback period for various motors of enhanced efficiency classes: the IE3, IE4 induction motors, the DOL PMSM, and the DOL SynRM. These parameters are calculated with respect to the basic case of using the IE2 motor in the pump unit. The comparison takes into account not only the efficiency of the motors at different pump loads but also the effect of their power factor on the cable and transformer losses. It is shown that taking this factor into account significantly affects the comparison for the studied motors. For example, it was shown that the DOL PMSM provides the greatest amount of energy savings over the life cycle despite the fact that its efficiency is not highest among the motors under consideration.

The analysis takes into account that the motors have different initial costs. The IE4 IM has an increased cost compared to the IE3 IM and the DOL SynRM due to the higher consumption of the main active materials: copper and electrical steel. The DOL PMSMs have the highest initial cost compared to the IMs and the DOL SynRM due to the use of expensive rare-earth magnets in its design. In addition, the rare-earth elements processing from raw ore is associated with significant environmental damage.

It is shown that the payback period of all considered energy efficient motors is less than 1 year. The use of an IM IE3 class motor would pay off in a very short term after a new pump unit was put into operation since its payback period is 2.2 month (0.18 years), which is less than that of IE4 IM and DOL PMSM (0.26 and 0.31 years, correspondingly). However, after 4 months (0.33 years) IE4 IM and DOL PMSM turn out to be more cost-effective than IM IE3. Estimated 20 years life cycle cost savings of the IE4 IM and the DOL SynRM motors have similar values: 12.8 and 12.5 k€, respectively, which is 9.9% and 9.7% higher than that of the IE2 IM. In the case of the IE3 IM, the value of 20 years life cycle cost was only 8.1 k€ or 6.3% higher than that of the IE2 IM, which is significantly less profitable compared to the IE4 IM and the DOL SynRM. The most profitable in the course of 20 years is the use of the DOL PMSM, as its life cycle savings is 14.2 k€, which is 10.9% higher than that of IE2-IM.

The analysis shows that the DOL SynRM provides energy and cost savings close to the more expensive the IE4 IM and the DOL PMSM. The IE4 IM gives only 0.2% higher savings over 20 years than the DOL SynRM. The DOL PMSM delivers 1.2% higher savings over 20 years than the DOL

SynRM. However, the DOL SynRM has the shortest payback period of 0.65 years, in case of a motor replacement in a pump unit in operation. The payback period for the DOL PMSM and the IE4 IM is slightly higher than that of the DOL SynRM and in both cases is about 0.78 years.

Based on the results of this study, it can be concluded that, at the present time, the use of IE4 motors is more profitable than the use of motors of classes IE2 and IE3. The cost-effectiveness of the use of direct-on-line synchronous motors of various types is also validated in this study.

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